University of Technology Sydney

School of Civil and Environmental Engineering

Faculty of Engineering and Information Technology

Behaviour of RC Beam-Column Connections Retrofitted with FRP Strips

by

Rijun Shrestha

BEng., GCertEng.

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CERTIFICATE OF AUTHORSHIP/ORIGINALITY

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Rijun Shrestha

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When I was doing my post-graduate study, I had never thought of taking it to the next level but it was Professor Bijan Samali, who inspired me to continue my studies and do a PhD degree. Dr Scott T. Smith then helped me to gain confidence in doing a PhD research when I met him and Professor Samali to discuss on a possible project. Therefore, I would like to express my gratitude to Professor Samali and Dr Smith for inspiring me in taking up this research.

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Doing a PhD has been a different experience. Unlike the normal degree through course work, you are working on your own most of the time and with little interaction with fellow researchers as they may be from complete different background. Fortunately, when I started my study, three fellow researchers, Seo Jin (Paul) Kim, Rajeev Kaul and Omar Otoom, also started their PhD and on similar projects dealing with FRP and Dr Mehran Ameli joined us a year later as a post-doctoral research fellow. As such, there were opportunities for interaction among us and having a research group dedicated to FRP had its own advantages. It was unfortunate that Rajeev, Omar and Dr Ameli had to leave early in pursuit of other commitments they had which made the last two years of the project not as interactive as it was in the first two years. The first year at the Black Friar's building and then on Level 23 with Rajeev, Paul and Omar is memorable. Also, guidance and expert advice provided by Dr Fook Choon Choi regarding use of ANSYS is highly appreciated.

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Conference Papers

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Shrestha, R., Smith, S.T. and Samali, B. (2008) "Effectiveness of strengthening RC beam-column connections in shear with vertical FRP strips", *Proceedings* (*CD Rom*), *Fourth International Conference on FRP Composites in Civil Engineering, CICE 2008,* 22-24 July, Zürich, Switzerland.

Shrestha, R. and Smith, S.T. (2007) "An experimental investigation on the strengthening of RC beam-column connections with FRP composites", *Proceedings, First Asia-Pacific Conference on FRP in Structures, APFIS 2007,* Hong Kong, China, 12-14 December, pp. 213-220.

Smith, S.T. and Shrestha, R. (2006) "A review of FRP-strengthened RC beam-column connections", *Proceedings, Third International Conference on FRP Composites in Civil Engineering, CICE 2006*, Miami, USA, 13-15 December, pp. 661-664.

Shrestha, R., Smith, S.T. and Saleh, A. (2006) "Finite element modelling of RC beam-column connections strengthened with FRP composites", *Proceedings (CD Rom), Eleventh Structural Faults and Repair Conference*, SF&R 2006, Edinburgh, Scotland, 13-15 June.

ABSTRACT

Reinforced concrete (RC) buildings designed prior to the implementation of seismic design codes were largely designed without structural details required for satisfactory seismic performance. These buildings are therefore more susceptible to damage in case of an earthquake and hence may require strengthening to meet current design standards. For instance, the majority of buildings that may require strengthening in Australia are those designed prior to the implementation of Australia's first earthquake design standard in 1979.

Non-seismic load designed RC framed structures may possess several inherent weaknesses when subjected to a seismic attack. One major design deficiency is inadequate or no transverse reinforcement (otherwise known as stirrups) in the joint region of the RC beam-column connections (herein referred to as connections) which may lead to joint shear failure in a seismic attack. It is important here to establish that a joint refers to the intersecting region of the column/s and beam/s while a connection refers to the joint region plus surrounding beam/s and column/s. Another inadequacy is the practice of not anchoring the bottom beam longitudinal bars which may lead to bar pull-out due to load reversal in the case of a seismic attack. The proportioning of the beam and column elements framing into the connection region may lead to the undesirable formation of a strong-beam-weak-column mechanism. In addition, plastic hinging may form in the beam or column adjacent to the joint region thus compromising the strength and integrity of the joint. Past earthquakes such as El Asnam (1980), Mexico (1985), San Salvador (1986), Loma Prieta (1989) and Turkey (1999) have shown the vulnerability of RC framed structures with inherent non-seismic load designed weaknesses to catastrophically collapse due to connection failure. The proper strengthening of connections with such inherent weaknesses is in urgent need in order to ensure the safe performance of RC connections under seismic attack.

Over the past decade or so, fibre reinforced polymer (FRP) composites have emerged as a viable solution for strengthening structures due to their superiority in strength-to-weight ratio, ease of handling and forming into shapes, and corrosion resistance when

compared with more traditional construction materials such as steel. Many experimental, analytical and numerical studies have been conducted on the strengthening of RC beams, columns, slabs and walls as well as various other structural elements with FRP. Many field applications have also been reported around the world. Significantly less research and field applications by comparison have been reported on the strengthening of RC connections with FRP composites.

Experimental studies on FRP-strengthened exterior and interior connections have demonstrated the ability of externally bonded FRP to rectify the inherent weakness of non-seismic load designed RC connections by enhancing the joint shear capacity, in addition to enhancing the flexural capacity and to also relocate the possible formation of plastic hinges in the beam away from the joint region, as well as to promote a strong-column-weak-beam failure mechanism. Most of these experimental studies, while extremely useful, have been concerned with the behaviour of the strengthened connection as a whole with less attention paid to the behaviour of the FRP strengthening itself. In addition, the distinct lack of numerical simulations and analytical models, by comparison, are hindering better understanding and the more widespread rational design of FRP-strengthened for RC connections.

The research reported in this dissertation focuses on the commonly occurring case of a shear strength deficient connection. Such connections are retrofitted or repaired with FRP strips however from herein such application of FRP will collectively be referred to as strengthening. The key aims of this project are to (i) experimentally observe and quantify the behaviour of FRP strengthening in FRP-strengthened connections, (ii) accurately simulate the experimental results produced in aim (i) using finite elements and identify the strengths and weakness of such numerical modelling, (iii) perform parametric studies with the calibrated numerical models, (iv) develop an analytical model which can rationally and reliably predict the behaviour of the FRP-strengthened connections, and (v) formulate a design approach which can be easily incorporated into future versions of existing FRP-strengthening design guidelines as well as new guidelines.

Initially a state-of-the-art review is conducted on the current state of knowledge pertaining to FRP-strengthened RC connections. Existing research is also systematically categorised for ease of reference and comparison and for identifying the various issues still requiring research attention. The experimental program then forms the heart of the project and considers the shear strengthening of virgin connections as well as the repair of damaged connections. A strength hierarchy dictating shear failure in the joint region (even after application of the FRP) is deliberately chosen in order to assess the effectiveness and limitation of the FRP strengthening. All test specimens are extensively instrumented and the majority of connections are tested under monotonic load which greatly enhances the ability to effectively monitor the behaviour of the FRP as well as the cracking behaviour of the connection. Two connections are also tested under cyclic loading in order to assess the energy absorption characteristics of the strengthening schemes.

Finite element models are developed for plain (RC connection without any FRP strengthening) and FRP-strengthened RC connections which are then used to perform parametric studies to analyse various parameters affecting the behaviour of the connections such as amount of FRP, location of the FRP strips and strength of concrete. Also, a simple analytical model is presented based on the finding of the tests which can accurately estimate the contribution of the FRP strengthening to the connection shear strength. Finally, recommendations are made for design of FRP strengthening of shear deficient RC connections and future research needs are identified.

NOTATION

β	=	orientation of FRP with respect to longitudinal axis of member
β_l	=	factor that relates magnitude of stress (or strain) in the column main bars to the average stress (or strain) at the column centre line
β_t	=	factor that relates magnitude of stress (or strain) in the beam main bars to the average stress (or strain) at the beam centre line
ε	=	strain in concrete at stress equal to σ
ε_o	=	concrete strain at ultimate compressive stress
ε_{cf}	=	concrete strain at the extreme fibre
ε_{co}	=	elastic strain limit for concrete
$\varepsilon_{F,e}$	=	effective strain of FRP at failure
ε_{frp}	=	strain in FRP at failure
ε_{frp}	=	average axial strain in the fibre direction at the peak load
ε_{p}	=	maximum permissible FRP strain
λ	=	ratio of maximum to effective bond length
v_n	=	the joint shear strength
θ	=	angle between the critical diagonal compression strut and column axis
θ	=	angle between critical diagonal crack and column axis
ρ	=	density of concrete
ρ_b	=	area ratio of longitudinal beam reinforcement
ρ_l	=	effective vertical reinforcement ratio
ρ_t	=	area ratio of horizontal stirrup in the joint
σ	=	concrete stress
σ_{axial}	=	column axial stress
a_s'	=	distance from compressive face to centroid of compressive steel reinforcement
A_{frp}	=	cross-sectional area of FRP

$A_{frp,i}$	=	cross-sectional area of FRP strip crossing the joint.
A_{sv}	=	cross-sectional area of steel shear reinforcement
b	=	joint width or depth of column
b_c	=	column width (i.e. the dimension of the column perpendicular to the face of the FRP strengthening)
b_j	=	joint width
C_b	=	tension force transferred to the joint region
D_f	=	stress distribution factor for FRP
d	=	joint depth
d_l	=	distance from the extreme compression fibre to the neutral axis
d_e	=	effective connection depth
d_w	=	depth of column
E_c	=	modulus of elasticity for concrete
E_F	=	modulus of elasticity of FRP
E_{frp}	=	modulus of elasticity of FRP
E_w	=	elastic modulus of the FRP
f_{by}	=	yield stress of beam reinforcement
f_c	=	concrete compressive strength
f_{cmax}	=	crushing strength of concrete
f_{ctm}	=	mean tensile strength of concrete
$f_{f,deb}$	=	maximum tensile stress in FRP sheet
f_{fl}	=	average normal stress in the FRP in longitudinal direction
f_{ft}	=	average normal stress in the FRP in transverse direction
f_{ftl}	=	shear stress in the FRP
f_l	=	average stress of longitudinal reinforcement of the column at mid height of the joint
f_t^b	=	average stress in beam reinforcement
f_t^s	=	average stress in stirrup
f_{yl}	=	yield stress of column reinforcement
f_{sy}	=	yield strength of steel shear reinforcement

$f_{u,i}$	=	stress in the FRP at failure
f'_c	=	ultimate compressive stress in concrete
f'_{cf}	=	tensile strength of concrete
h	=	column depth
h_0	=	effective depth of section
h_{b0}	=	effective depth of beam (i.e. distance from compressive face to centroid of beam steel tension reinforcement)
h_c	=	total column depth (dimension in the same plane as the FRP strengthening)
h_j	=	total joint depth (equals the depth of the beam h_b)
L_b	=	distance of beam tip load from the column centre line
l_b	=	bond length
l_c	=	length of the column between the points of contra flexure
L_e	=	effective bond length
L_{max}	=	maximum bond length
$M_{b,centre}$	=	moment at the joint centre
N	=	column axial force
n	=	number of FRP layers
N_h	=	beam axial force
N_v	=	compressive axial load of the column
P_b	=	beam tip load
Q_{ij}	=	elements of FRP stiffness matrix
s	=	centre-to-centre spacing of steel shear reinforcement
T	=	tensile forces transferred to the joint
T_b	=	tension force transferred to the joint region by beam
$T_{b,s}$	=	tensile force due to steel in tension
$T_{b,frp}$	=	tensile force due to FRP
t_F	=	thickness of FRP
t_w	=	wrap thickness
V_b	=	beam shear force
V_{col}	=	column shear force
V_c	=	contribution of concrete to the joint strength

V_{frp}	=	contribution of FRP to the joint strength
V_j	=	joint shear force
v_j	=	joint shear stress
V_{jh}	=	horizontal shear force across the joint
v_{jh}	=	horizontal shear stress across the joint
V_{jv}	=	vertical joint shear force across the joint
v_{jv}	=	vertical joint shear stress
V_s	=	contribution of transverse joint reinforcement to the joint strength
V_u	=	shear strength of the joint

LIST OF CONTENTS

LIST OF TABLES

LIST OF FIGURES